



Assessment of the exposure to *Echinococcus multilocularis* associated with carnivore faeces using real-time quantitative PCR and flotation technique assays

Abdou Malik da Silva, Sandra Courquet, Francis Raoul, Dominique Rieffel, Patrick Giraudoux, Laurence Millon, Jenny Knapp

► To cite this version:

Abdou Malik da Silva, Sandra Courquet, Francis Raoul, Dominique Rieffel, Patrick Giraudoux, et al.. Assessment of the exposure to *Echinococcus multilocularis* associated with carnivore faeces using real-time quantitative PCR and flotation technique assays. *International Journal for Parasitology*, 2020, 50 (14), pp.1195-1204. 10.1016/j.ijpara.2020.07.008 . hal-03038760

HAL Id: hal-03038760

<https://hal.science/hal-03038760>

Submitted on 15 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

**Assessment of the exposure to *Echinococcus multilocularis* associated with carnivore
faeces using real-time quantitative PCR and flotation technique assays**

Abdou Malik Da Silva^a, Sandra Courquet^{a,b}, Francis Raoul^a, Dominique Rieffel^a, Patrick
Giraudoux^a, Laurence Millon^{a,b}, Jenny Knapp^{a,b,*}

^a *Chrono-Environnement, UMR UBFC/CNRS 6249, University of Bourgogne Franche-Comté,
25030 Besançon, France*

^b *Department of Parasitology-Mycology, University Hospital of Besançon, 25030 Besançon, France*

*Corresponding author. Tel.: +33 363082274. E-mail address: jknapp@univ-fcomte.fr

17 **Abstract**

18 The eggs of *Echinococcus multilocularis*, the infectious stage, are spread into the environment
19 through wild and domestic carnivore faeces. The spatial location of the faeces containing infective
20 *E. multilocularis* eggs is a key parameter for studying areas of exposure and understanding the
21 transmission processes to the intermediate hosts and humans. *Echinococcus multilocularis* faecal
22 prevalence is often assessed by detecting *E. multilocularis* DNA, not necessarily eggs. This work
23 aimed to determine the percentage of faeces containing *E. multilocularis* eggs in a rural town and its
24 surroundings and whether this level of precision is relevant in assessing exposure to *E.*
25 *multilocularis*. For this purpose, we developed a combined molecular and microscopic approach to
26 investigate the *E. multilocularis* exposure of potential hosts in the environment from field-collected
27 carnivore faeces. Carnivore defecation patterns were then spatialized to study the spatial
28 distribution of *E. multilocularis*. Faeces were screened for *E. multilocularis* DNA using a specific
29 real-time quantitative PCR (qPCR). *Echinococcus multilocularis* eggs were morphologically
30 identified from *E. multilocularis*-specific qPCR-positive faeces after sucrose flotation and
31 individually confirmed through specific PCR and sequencing. The spatial distribution of *E.*
32 *multilocularis* was studied using Kulldorff statistics. *Echinococcus multilocularis* eggs were
33 identified mostly in fox faeces positive for *E. multilocularis* DNA by qPCR ($n=27/70$) and only
34 from 1 of 15 copro-samples from dogs and 1 of 5 from cats. The faecal prevalence of *E.*
35 *multilocularis* DNA and eggs was overdispersed, with the same geographical patterns. These data
36 suggest that *E. multilocularis* DNA and/or egg detection in carnivore faeces, mainly that of foxes, is
37 appropriate in ecological studies of *E. multilocularis* transmission.

38

39 *Keywords:* *Echinococcus multilocularis*, Egg, Definitive host, Copro-qPCR diagnostic, Flotation,
40 Spatial distribution

41

42 **1. Introduction**

43 The larval stage of the cestode *Echinococcus multilocularis* is responsible for alveolar
44 echinococcosis (AE), an expanding, potentially lethal, zoonosis that occurs only in the northern
45 hemisphere, including large areas of Asia, Europe, and North America (Deplazes et al., 2017). The
46 lifecycle is mainly sylvatic, based on predator-prey interactions between wild and domestic
47 carnivores acting as definitive hosts, and small rodents as intermediate hosts. The adult worms live
48 in the small intestine of carnivores and produce the infectious form at sexual maturity, the egg,
49 eliminated into the environment with faeces during the patent period. Development of the larval
50 stage of the parasite following the ingestion of eggs causes AE in humans. In Europe, *E.*
51 *multilocularis* eggs have only rarely been identified in dog and cat faeces (Dyachenko et al., 2008;
52 Deplazes et al., 2011; Umhang et al., 2012, 2014, 2015; Knapp et al., 2016a). The red fox (*Vulpes*
53 *vulpes*) has been identified as the main definitive host of *E. multilocularis*, in which the parasite has
54 experimentally shown a high reproduction rate and high biotic potential, whereas domestic
55 carnivores, notably the cat, likely excrete few or no eggs (Kapel et al., 2006; Hegglin and Deplazes,
56 2013; Umhang et al., 2015; Knapp et al., 2018).

57 The use of carnivore stools in ecological investigations on *E. multilocularis* transmission
58 seems appropriate, as stool contamination is representative of environmental contamination by the
59 infectious form of the parasite and it is the source of human exposure (Conraths and Deplazes,
60 2015; Knapp et al., 2018). In addition, the spatial location of the faeces containing infective *E.*
61 *multilocularis* eggs is a key parameter for studying areas of risk and understanding the transmission
62 processes to the intermediate hosts and humans, to propose appropriate prevention or control
63 measures (Knapp et al., 2018). Moreover, the analysis of faecal samples is a non-invasive approach,
64 allowing the preservation of animal populations, essential when studying pets and ethically more
65 acceptable for wild animals.

66 The spatial distribution of carnivore faeces and *E. multilocularis* prevalence appear
67 heterogeneous and aggregate in micro-foci over large areas including historically and newly
68 endemic rural and urban sites. The reasons are in part linked to the defecation behaviour of the
69 definitive hosts. For instance, micro-local hotspots of high *E. multilocularis* prevalence in fox
70 faeces were detected in different rural situations in a study carried out in an eastern region of France
71 (Knapp et al., 2018). Moreover, at a local level, *E. multilocularis*-positive faeces were found in
72 19/94 sampled kitchen gardens studied (Pouille et al., 2017). In a North American urban setting, *E.*
73 *multilocularis* prevalence in the faeces of coyotes varied significantly across the study area (Liccioli
74 et al., 2014). In a rural context in China, *E. multilocularis* environmental contamination via dog
75 faeces was focused where dogs defecated inside villages (Vaniscotte et al., 2011). Given the close
76 proximity of humans and the main definitive host of *E. multilocularis* in rural settings, this
77 environmental overdispersal can potentially be of major public health importance. However, *E.*
78 *multilocularis* prevalence is often assessed by detecting *E. multilocularis* DNA, not necessarily
79 eggs. Furthermore, the sporadic copro-sample collection may lead to failure to detect the parasite
80 and a misestimation of environmental contamination by *E. multilocularis* via carnivore faeces.

81 The development and optimization of multiplex real-time PCR techniques, based on the
82 amplification of specific mitochondrial DNA targets, has resulted in the very sensitive and rapid
83 detection of host species and zoonotic parasites such as *E. multilocularis* in faeces collected from
84 the environment (Farrell et al., 2000; Nonaka et al., 2009; Knapp et al., 2014, 2016b). Molecular
85 tools (PCR or real-time quantitative PCR (qPCR)) detect the genetic material in faeces not only
86 from eggs but also from cells or tissue fragments shed by the worm present in the digestive tract of
87 the infected animal (Al-Sabi' et al., 2007) and other traces of the parasite in transit. The feeding
88 behaviour and coprophagia common in certain carnivore species such as dogs may explain the
89 innocuous passage of parasitic elements, and thus the detection of parasitic DNA, in the digestive
90 system of these animals (Frenkel and Parker, 1996; Fahrion et al., 2011; Nijssen et al., 2015).
91 *Echinococcus multilocularis* DNA may also originate directly from the digested metacestode due to

92 predation of infected rodents (Umhang et al., 2015). These events can all potentially lead to
93 overestimation, to an unknown extent, of the parasitic prevalence in faeces by molecular detection
94 techniques. Thus, the detection of eggs in stool material is still a key step in the assessment of the
95 environmental exposure of intermediate hosts or humans to *E. multilocularis*.

96 Eggs may be concentrated by flotation techniques and identified at the family level
97 (Taeniidae) based on their morphological characteristics (Mathis et al., 1996; Dryden et al., 2005)
98 ,and PCR on isolated egg DNA remains the method of choice for the species-level diagnosis
99 (Gasser et al., 1993).

100 This work aimed to determine the percentage of faeces containing *E. multilocularis* eggs in a
101 rural town and its surroundings and whether this level of precision is relevant in assessing exposure
102 of the intermediate hosts to *E. multilocularis*. For this purpose, we periodically collected carnivore
103 faeces in order to obtain suitable samples for parasite detection. We developed a combined
104 molecular and microscopic approach to investigate exposure of potential hosts to *E. multilocularis*
105 in the environment from field-collected carnivore faeces. This strategy is first based on the
106 screening of *E. multilocularis* DNA in faeces, using qPCR and then the identification of *E.*
107 *multilocularis* eggs in positive qPCR samples by a flotation technique, confirmed by specific PCR.
108 Then, carnivore defecation patterns were spatialized to compare the local distribution of *E.*
109 *multilocularis* DNA and eggs in contaminated faeces.

110

111 **2. Materials and methods**

112 *2.1. Copro-sampling*

113 Faeces were collected every 2 months between March 2017 and November 2018 in a village
114 and its surroundings in the eastern part of France (006°26'46"E, 46°56'53"N), in order to regularly
115 obtain fresh material. This site was located in an historic endemic area for *E. multilocularis*

116 (Combes et al., 2012; Piarroux et al., 2013, 2015). The studied area has a surface of 5.28 km², with
117 a density of 25 inhabitants per km², and is located at an average altitude of 971 m above sea level in
118 a predominantly agricultural landscape in which the proportion of permanent grassland to total land
119 is 52% (see the 2010 General Agriculture Census (RGA) from the Ministry of Agriculture, France,
120 <http://recensement-agricole.agriculture.gouv.fr/>). It has a continental climate, with long, cold,
121 snowy winters. Average temperatures range from -2.2 to 15.1°C with average rainfall of 1,317
122 mm/year (www.meteofrance.com). All sampled carnivore faeces were collected from the study area
123 access roads within the administrative limits (along a predetermined circuit of 25 km, Fig. 1). Fox,
124 dog, cat, mustelid or undetermined faeces were initially identified in the field by observing their
125 physical characteristics (shape, size, composition). All sampled faeces were geolocated with a
126 Global Positioning System (GPS) tracking device, with a precision of ± 10 m. Those were collected
127 in an individual plastic bags and were stored for 7 days at – 80°C for decontamination to prevent
128 human infection, and then at – 20°C before laboratory analyses.

129

130 2.2. Faecal DNA extraction and qPCR protocols for carnivore host faecal test and *E. multilocularis* 131 diagnostic tests

132 Faecal DNA was extracted from a 0.5 g sample (Knapp et al., 2014) and purified using the
133 QIAmp Fast DNA Stool Kit (Qiagen, Hilden, Germany) following the manufacturer's
134 recommendations, performed on a QIAcube automaton (Qiagen, Hilden, Germany), a robotic
135 workstation for automated purification of DNA.

136 A host faecal qPCR test was performed on the copro-DNA to identify the carnivore host.
137 The test was carried out as described above and was based on amplification of a fragment of the
138 *cytB* gene for *Vulpes vulpes* (fox), *Canis familiaris* (dog), and *Felis catus* (cat) (Knapp et al.,
139 2016b). This molecular identification of host species used as reference was compared with the

140 identification from morphological criteria (described above) in order to verify the accuracy of faecal
141 identification in the field.

142 DNA extracts were tested in an *E. multilocularis*-specific qPCR for the presence of *E.*
143 *multilocularis* DNA, in duplicate, based on the amplification of a portion of the mitochondrial *rrnL*
144 gene (Knapp et al., 2014, 2016b) (*rrn-E. multilocularis* forward primer 5'-
145 CTGTGATCTTGGTGTAGTAGTTGAGATTT-3', *rrn-E. multilocularis* reverse primer 5'-
146 GGGGTCAATCACAACAACCC-3', *rrn-E. multilocularis* probe 5'- FAM-
147 TGGTCTGTTCGACCTTTTTCAGCCTCCAT-TAMRA -3') for PCR products of 202 bp.

148 The presence of inhibitory factors was tested in the two previous qPCRs using the Alea
149 qPCR control tool (Alea forward primer 5'-CCTAAAAATGTCTATGATTGGTCCACTA-3', Alea
150 reverse primer 5'-GGGAGTACCTTGCCATACAAAATT-3', Alea probe 5'-VIC-
151 TTAAATCAACTCCTAAATCCGCGCGATAGG-TAMRA-3') at a concentration of 6.10^{-6} ng/ μ l,
152 corresponding to 1,000 plasmid copies/ μ l of the internal control (Knapp et al., 2016b).

153 DNA-free extraction controls (extraction from only kit reagents), PCR-positive (DNA
154 extracts from *E. multilocularis* worms) and -negative (ultra-pure water instead of DNA extract)
155 controls were used to ensure there was no contamination during the DNA extraction and the qPCR
156 steps.

157 The qPCRs were performed for 45 cycles and reactions with quantitative cycle (Cq)
158 numbers < 45 cycles were considered to be positive for *E. multilocularis* by qPCR and Cq < 30 for
159 the species detected among the three targeted carnivore species in the faecal qPCR. The presence of
160 PCR inhibitors was noted on the basis of the duplex *E. multilocularis* /Alea qPCR results,
161 considering a Cq > 37 as the threshold beyond which the PCR inhibitors interfered with the PCR
162 process (Knapp et al., 2016b). All samples were tested in duplicate by qPCR.

163

164 2.3. Isolation of parasite eggs from faeces

165 All positive faeces from the *E. multilocularis*-specific qPCR screening and a portion of
166 randomly selected negative faeces, as controls, ($n = 25$) were subjected to a sucrose flotation
167 technique as described in Matsuo and Kamiya (2005) and Escotte-Binet et al. (2019) to concentrate
168 and isolate the parasite eggs, based on differential specific gravity (SG) between the eggs and
169 particles. Briefly, the protocol consists of dispersing 5 g of faeces in 20 ml of 0.1% Tween 80 by
170 vortexing to separate the eggs from the organic particles. After a centrifugation step (2,500 g, 10
171 min), the pellet is resuspended in distilled water and deposited on a sucrose solution (SG = 1.27) to
172 float the eggs. Then the supernatant is concentrated in a volume of < 1 ml after centrifugation.

173

174 2.4. Microscopic observation and sampling of individual *E. multilocularis* eggs

175 All flotation supernatants were examined using a Leica DMI3000-B micromanipulator (Leica
176 Microsystems, Wetzlar, Germany) equipped with an inverted microscope to identify taeniid eggs at
177 a 400X magnification. The observed taeniid eggs were picked individually with micropipettes
178 integrated into the micromanipulator and put in approximately 100 μ l of distilled water in
179 individual microtubes. For each positive flotation sample, DNA from up to five individual taeniid
180 eggs was extracted using the QIAmp DNA Mini Kit (Qiagen, Hilden, Germany) in an elution
181 volume of 50 μ l following the manufacturer's instructions. However, the lysis step was extended
182 from 1-3 h to overnight. The resulting DNA was used to confirm the *E. multilocularis* egg
183 identification by two PCRs: the *E. multilocularis*-specific qPCR described above and the *E.*
184 *multilocularis*-specific PCR EMH15/H17, confirmed by electrophoresis. The *E. multilocularis*-
185 specific PCR EMH15/H17 is based on the amplification of a portion of the mitochondrial 12S
186 rRNA gene (Dinkel et al., 1998; Stieger et al., 2002; Georges et al., 2004) (EM-H15, forward
187 primer: 5'-CCATATTACAACAATATTCCTATC-3', EM-H17, reverse primer: 5'-
188 GTGAGTGATTCTTGTTAGGGGAAG-3') for an expected PCR product size of 200 bp. Then,
189 several PCR products ($n = 6$) were randomly selected and sequenced by the Sanger method to

190 confirm the *E. multilocularis* diagnosis (Sanger et al., 1992). The nucleotide sequences obtained
191 were characterized by comparison with an *E. multilocularis* nucleotide sequence reference in
192 GenBank using the online genetic databases and the Basic Local Alignment Search Tool (BLAST)
193 available on the NCBI website.

194 In addition, for each negative flotation sample, the supernatants were extracted and
195 subjected to *E. multilocularis*-specific qPCR to confirm the microscopic observations (see Fig. 2 for
196 a synopsis of the complete protocol).

197

198 2.5. Determination of flotation technique sensitivity

199 The effectiveness of the sucrose flotation technique followed by microscopic observation
200 and detection with *E. multilocularis*-specific qPCR (described above) was evaluated by testing it in
201 duplicate series of faecal-free *E. multilocularis* DNA samples (5 g) spiked with 10 *E. multilocularis*
202 eggs ($n=3$), five *E. multilocularis* eggs ($n=3$), three *E. multilocularis* eggs ($n=3$) and one *E.*
203 *multilocularis* egg ($n=3$). These spiked samples were frozen at -80°C for 7 days before testing. The
204 faecal samples were obtained from the colon of captive foxes exhibiting no worms of the *Taenia*
205 genus nor *E. multilocularis* at the experimental station of the ANSES laboratory, France.
206 *Echinococcus multilocularis* eggs were obtained from a faecal sample from the colon of a naturally
207 infected fox and confirmed with *E. multilocularis*-specific qPCR.

208

209 2.6. Statistical and spatial data analysis

210 *Echinococcus multilocularis* faecal prevalence between the various carnivore species was
211 compared using the Fisher's exact test. The non-parametric Mann-Whitney U Test was used to
212 compare the Cq values between *E. multilocularis* qPCR-positive faeces, with or without *E.*
213 *multilocularis* eggs detected. A Receiver Operating Characteristic (ROC) curve analysis was used

214 to estimate the ability of the *E. multilocularis*-specific qPCR (*E. multilocularis* DNA screening in
215 faeces) to differentiate faeces containing *E. multilocularis* eggs or not. An optimal threshold value
216 was determined by maximizing the Youden index. Faeces with a Cq higher than the optimal
217 threshold value were classified as *E. multilocularis* egg-negative, whereas samples with a Cq lower
218 than the optimal threshold value were classified as *E. multilocularis* egg-positive (Fluss et al.,
219 2005). ROC, area under ROC curve (AUC) and the optimal threshold value were calculated using
220 the *pROC* R package (Robin et al., 2011).

221 For statistical tests, differences were considered significant for $P \leq 0.05$.

222 The spatial distributions of carnivore faeces and *E. multilocularis* faecal occurrence were
223 mapped on orthophotos (BD Ortho version 2 of the ‘Institut Géographique National’, France, with a
224 50 cm resolution as background).

225 The randomness of the distribution of the *E. multilocularis* faecal prevalence was tested
226 using a spatial scan statistic developed by Kulldorff and implemented in SatScan v9.6 software
227 (Kulldorff and Nagarwalla, 1995). We tested the null hypothesis that the number of faeces
228 containing *E. multilocularis* DNA or eggs follows a binomial distribution along the predetermined
229 circuit. In SatScan, we used the Bernoulli Model, with the cases defined as faeces which were found
230 to contain *E. multilocularis* DNA or eggs and the controls as negative faeces. Kulldorff’s method
231 places a circular window on the map and moves the circle centre over each point location so that the
232 window includes different sets of neighbouring points at different positions. At each point location,
233 the radius of the circle increases continuously from zero to a maximum radius, defined by the user
234 and defaulted in this study to a radius containing at most 50% of the total number of points.
235 Potential clusters were detected by calculating a likelihood ratio for each circle, comparing an
236 expected number of cases (under the null hypothesis) with the observed number of cases in and
237 outside the window. The most likely cluster is the circle with the maximum likelihood ratio among
238 all radius circles at all possible locations.

239 Computations were performed and graphical displays were generated using R 3.5.1 (R Core
240 Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical
241 Computing, Vienna, Austria, <https://www.R-project.org>) with the packages foreign 0.8-70 (R Core
242 Team (2017). Foreign: Read Data Stored by 'Minitab', 'S', 'SAS', 'SPSS', 'Stata', 'Systat', 'Weka',
243 'dBase', ..., <https://CRAN.R-project.org/package=foreign>), rgdal 1.3-9 (Bivand, R., Keitt, T.,
244 Rowlingson, B., Pebesma, E., Sumner, M., Hijmans, R., Rouault, E., Warmerdam, F., Ooms, J.,
245 Rundel, C., 2019. rgdal: Bindings for the "Geospatial" data abstraction library) and the
246 geographical information system Quantum GIS 3.2.3-Bonn (QGIS Development Team, 2018.
247 QGIS Geographic Information System, <http://www.qgis.com>). Kulldorff's statistics were computed
248 using SatScan v9.6 March 2018 (<https://www.satscan.org>).

249

250 2.7. Data accessibility

251 Raw data are available in Mendeley Data, DOI: <https://dx.doi.org/10.17632/bhzccxfy9c.3>.

252

253 3. Results

254 3.1. Host species identity of faeces collected in the field

255 We collected 814 faecal samples from March 2017 to November 2018. In total, 763 faecal
256 samples (93.7% of the sampling) were identified by the host faecal qPCR test, including 278 fox
257 faeces (34.15%), 431 dog faeces (52.95%), and 54 cat faeces (6.63%).

258 The morphological assessment made on fox, dog and cat faeces was confirmed by species
259 qPCRs for 68%, 86% and 52% of the copro-samples, respectively (Table 1). For mustelid faeces
260 identified on morphological criteria, 56% and 28% of samples were reassigned to fox and dog

261 stools, respectively, by molecular analysis. Most of the undetermined faeces in the field were
262 identified by molecular assessment (87.5%).

263 The host faecal test was unsuccessful for 51 faecal samples for which identification was
264 made based on morphological criteria. This affected 31 fox, 14 dog, one cat, four mustelid, and one
265 undetermined stools (Table 1).

266 Only four samples (0.5% of all samples analysed) contained PCR inhibitors based on duplex
267 *E. multilocularis*/Alea qPCR results.

268

269 3.2. *Echinococcus multilocularis* in carnivore hosts

270 3.2.1. Validation of the sucrose flotation protocol for frozen *E. multilocularis* eggs

271 When testing naive frozen copro-samples of 5 g spiked with 10 *E. multilocularis* eggs, a
272 microscopic observation and a positive *E. multilocularis* qPCR signal were obtained for all samples
273 after the sucrose flotation technique, corresponding to 100% sensitivity (Table 2). Average Cq
274 values ranged from 30.73 ± 0.08 for 10 eggs to 37.72 ± 0.16 for one egg. When using five eggs, then
275 one egg, sensitivity decreased from 66.7% to 33.3% for the *E. multilocularis* qPCR.

276

277 3.2.2. *Echinococcus multilocularis* DNA and egg prevalence in carnivore faeces

278 We detected *E. multilocularis* DNA in 96 faeces samples (11.8% of the collection, 95%
279 Confidence interval (CI): 9.7-14.3%). *Echinococcus multilocularis* DNA was detected significantly
280 more frequently in fox faeces (25.2%, 95% CI: 20.3-30.8%) than cat faeces (9.3%, 95% CI: 3.5-
281 21.1%) or dog faeces (3.5%, 95% CI: 2.0-5.8%) (Table 3, Fisher's exact test, $P < 0.0001$).

282 Among the 96 carnivore faecal samples containing *E. multilocularis* DNA, 32 (33.3%) were
283 found to contain *E. multilocularis* eggs, based on the sucrose flotation technique. The identification

284 of *E. multilocularis* was confirmed by *E. multilocularis* specific qPCR performed on DNA extracts
285 from five individual taeniid eggs isolated from each flotation-positive faecal sample, for which
286 between one and five were positive, with a mean Cq of 34.2 ± 1.46 ($n = 52$). All selected PCR
287 EMH15/H17 products ($n = 6$, PCR EMH15/H17 positive from *E. multilocularis* eggs isolated from
288 one dog, one cat, one undetermined host, and three fox stools) were confirmed to be *E.*
289 *multilocularis*, with 100% identity to the *E. multilocularis* reference sequence (GenBank accession
290 number **MK116545.1**).

291 Eggs were observed mostly in fox faeces ($n = 27/70$), one of five cat faeces, one of 15 dog
292 faeces, and three of six qPCR-undetermined host faeces (Table 3, Fisher's exact test, $P < 0.0001$).
293 Those three faecal samples were identified morphologically as two fox and one dog stool.

294 All selected *E. multilocularis* qPCR-negative faeces ($n = 25$) did not contain *E.*
295 *multilocularis* eggs, as their flotation supernatants were also negative by *E. multilocularis* qPCR,
296 except for one sample that had an average Cq of 37.34.

297

298 3.3. Relationship between the *E. multilocularis*-specific qPCRs for *E. multilocularis* egg-positive 299 and egg-negative faeces

300 Comparison of the Cq values obtained from *E. multilocularis*-specific qPCR performed on
301 carnivore faeces showed that, among positive faeces, the median Cq of the faeces not containing *E.*
302 *multilocularis* eggs was higher than that of the faeces containing *E. multilocularis* eggs: 38.92
303 versus 36.9. The distributions of Cq values between *E. multilocularis* qPCR-positive faeces with or
304 without *E. multilocularis* eggs differed significantly (Fig. 3A, non-parametric Mann-Whitney test,
305 $W = 1511$, $P < 0.001$). All but two faecal samples with a Cq less than 33.62 which had taeniid eggs
306 observed under a microscope, confirmed *E. multilocularis* by *E. multilocularis*-specific qPCR and
307 PCR (Fig. 3A). However, the ROC curve showed that the Cq values had only a weak ability to
308 differentiate samples containing *E. multilocularis* eggs and those without (AUC = 0.73, 95% CI:

0.614-0.847). Beyond the optimal threshold Cq of 38.36, corresponding to a sensitivity of 81% (95% CI: 66-94%) and a specificity of 69% (95% CI: 58-80%), most of the samples were negative by flotation (88%) (Fig. 3B).

3.4. Spatial distribution of *E. multilocularis* DNA and eggs via carnivore faeces

Domestic carnivore faeces (in particular, dog) were more prominent downtown than outside the village (Fig. 4C). Fox faeces were mostly found outside the village but some were also found inside (Fig. 4B).

Kulldorff's statistics showed two significant spatial clusters for *E. multilocularis* DNA-positive faeces and *E. multilocularis* egg-positive faeces for all carnivores pooled, located in the same areas in both cases. The *E. multilocularis* DNA faecal prevalence was clearly overdispersed, with a high-rate cluster ($P = 1.4 \times 10^{-6}$) located in the western part of the site but near the centre and a low-rate cluster ($P = 0.02$) in the eastern part (Fig. 4Aa). The faecal prevalence of *E. multilocularis* eggs showed significant clusters (high rate: $P = 10^{-9}$, low rate: $P = 4.75 \times 10^{-3}$) within the same geographical locations as those for *E. multilocularis* DNA faecal prevalence (Fig. 4Ab and 4Aa). For fox, *E. multilocularis* DNA-positive faeces (high rate: $P = 0.01$, low rate: $P = 0.02$) and *E. multilocularis* egg-positive faeces (high rate: $P = 0.002$, low rate: $P = 0.01$) were also aggregated (Fig. 4Ba and 4Bb). *Echinococcus multilocularis* contamination in domestic carnivores was not found to be clustered, likely due to the low number of positive samples (Fig. 4C). Contamination clusters were due to the high rate of contamination in fox faeces.

4. Discussion

This study focused on collecting evidence of *E. multilocularis* eggs in carnivore faeces in which *E. multilocularis* DNA was first detected by *E. multilocularis*-specific qPCR. The *E.*

333 *multilocularis* DNA and egg detection methods are notably effective in the patent phase of infection
334 (Al-Sabi' et al., 2007). DNA detection is possible but remains uncertain during the pre-patent and
335 post-patent periods due to irregular excretion of tissue or eggs (Deplazes et al., 2003). Here, the *E.*
336 *multilocularis* qPCR Cq values were significantly lower for samples in which eggs were present
337 than for flotation-negative samples, implying a larger amount of *E. multilocularis* DNA in *E.*
338 *multilocularis* qPCR-positive faeces. Our results suggest that in our protocol (DNA extraction and
339 qPCR protocol), faeces for which the *E. multilocularis* qPCR Cq values were less than 33.62 were
340 likely to contain *E. multilocularis* eggs. The effectiveness of the key step of DNA extraction from
341 taeniid or *E. multilocularis* eggs using a kit with only chemical lysis was previously demonstrated
342 (Štefanić et al., 2004; Davidson et al., 2009; Øines et al., 2014; Umhang et al., 2017). This Cq value
343 is very close to the mean *E. multilocularis* qPCR Cq of a DNA extract from one *E. multilocularis*
344 egg (34.2 ± 1.46). In a previous study, the detection limit of PCR targeting mitochondrial DNA (*E.*
345 *multilocularis*, *Echinococcus granulosus*, and that from single eggs of other tainiids), was estimated
346 to be 33 copies (Trachsel et al., 2007). Conversely, no conclusion can be drawn concerning the
347 presence/absence of *E. multilocularis* eggs in faeces with *E. multilocularis* qPCR Cq values ranging
348 from 33.62 to 38.36, the maximum beyond which most of the samples were negative. This
349 maximum corresponds to a mean *E. multilocularis* qPCR Cq of a DNA extract of faeces (500 mg)
350 experimentally spiked with one *E. multilocularis* egg (37.6 ± 1.34) (Knapp et al., 2014). The
351 absence of eggs in this interval could be justified by a high concentration of *E. multilocularis*-free
352 DNA. This is probably related to random sampling bias. Indeed, the *E. multilocularis* qPCR was
353 performed from only 0.5 g of faeces and the flotation technique from 5 g. In cases of low-grade
354 infection, this small subsample size would be more likely to contain no eggs. This could also
355 explain the weak ability of the *E. multilocularis* qPCR to differentiate samples containing *E.*
356 *multilocularis* eggs and those without. The *E. multilocularis* qPCR performed directly on carnivore
357 faeces probably detects more *E. multilocularis*-free DNA than *E. multilocularis* eggs. It appears that
358 flotation is necessary to assess exposure to *E. multilocularis* associated with carnivore faeces in the

environment. The sucrose flotation method combined with microscopical observation and qPCR detection used in this study proved to have sensitivity of 100% for the detection of 10 *E. multilocularis* eggs in 5 g of frozen copro-samples. Additionally, the sucrose flotation method enabled the potential recovery of only one egg in 5 g of faeces. Moreover, a flotation sample with no eggs gave a mean Cq of 37.34, demonstrating the presence of trace amounts of *E. multilocularis* DNA in the supernatant. The choice of the sucrose solution was justified by its safety and neutrality on parasitic elements, which can facilitate the recognition of eggs under the microscope after flotation. For instance, zinc chloride (SG=1.42), although more effective in floating eggs, could potentially alter the structural integrity of oocysts (Escotte-Binet et al., 2019) and frozen taeniid eggs (our personal observations). It is also very hazardous to human and environmental health (National Center for Biotechnology Information. PubChem Database., 2005. Zinc chloride, CID=5727. <https://pubchem.ncbi.nlm.nih.gov/compound/Zinc-chloride#section=Safety-and-Hazards>). On the other hand, some *E. multilocularis* qPCR results on isolated taeniid eggs were negative, likely related to the fact that other taeniid species can be found in carnivore intestines (Umhang et al., 2012; Li et al., 2013; Umhang et al., 2014, 2015; Karamon et al., 2019; Tylkowska et al., 2019). The individual isolation of eggs offers the possibility to non-invasively study the genetic diversity of the parasite in the same carnivore host faeces using the tandemly repeated microsatellite marker EmsB (Bart et al., 2006; Knapp et al., 2007, 2009; Umhang et al., 2014; Valot et al., 2015) and avoid complex analysis of egg or DNA pools (Carlsgart et al., 2008).

The use of species-specific qPCRs made it possible to identify the carnivore species for 763 of the 814 faeces samples collected, for a success rate of 93.7%. According to this molecular method, dog and fox faeces were better identified in the field than cat and mustelid faeces. Our results indicate that morphological identification of copro-material remains uncertain. Confirmation by a molecular reference technique is advisable to understand the relative contribution of each definitive species to environmental contamination (Pouille et al., 2017; Knapp et al., 2018). Only 0.5% of all analysed samples contained PCR inhibitor agents. Knapp et al. (2018) reported a similar

385 success rate (94.3%) but a higher rate of faeces containing inhibitors (9.7%). In our study, the
386 frequent sampling of faeces probably allowed us to obtain fresher samples, less subject to
387 environmental hazards and DNA degradation than copro-samples obtained by sporadic collection
388 (Kovach et al., 2003; Nonaka et al., 2009). Improved sampling conditions and the use of specific
389 kits for DNA extraction reduce the presence of PCR inhibitors and thus increase the sensitivity and
390 specificity of qPCR methods for species identification from stools (Al-Sabi' et al., 2007; Knapp et
391 al., 2014).

392 More than half of the faeces collected among domestic carnivores were from dogs versus
393 only 7% for cats. These faeces were found mostly in the centre of the village near houses. Fox
394 faeces accounted for 1/3 of all samples and were found in the centre and surrounding area. The
395 presence of fox faeces in proximity to humans is not surprising, as several studies have reported that
396 foxes approach human dwellings at night in rural areas to feed (Janko et al., 2012; Krauze-Gryz et
397 al., 2012; Scott et al., 2014), which was especially noticed in the study site (Knapp et al., 2018).
398 However, *E. multilocularis* DNA was detected in 25% of fox faeces (70/278) versus only 4%
399 (15/431) of dog faeces and 9.3% (5/54) of cat faeces. This relatively high prevalence of *E.*
400 *multilocularis* DNA in cat faeces was observed (4/43; 9.3%) in an endemic area in the north-eastern
401 part of France (Knapp et al., 2016a). This observation could be due to the small number of samples
402 collected or a possible multiple copro-sampling of the same or a few infected cats. In foxes and
403 dogs, similar findings were reported for the same study site in 2012 and 2013 (Knapp et al., 2018).
404 Indeed, *E. multilocularis* DNA was detected in 25.85% (61/236) of fox faeces compared with
405 1.46% (3/205) of dog faeces. Fox faeces collected from 94 vegetable gardens located in the
406 northeast of France were also reported to be the most contaminated, with a rate of 35% (24/69)
407 versus 11% (2/18) for dog faeces and 7% (6/86) for cat faeces (Pouille et al., 2017). In light of the
408 reported prevalence of *E. multilocularis* DNA, these studies, as well as ours, confirm the high risk
409 of transmission of *E. multilocularis*, associated mainly with foxes, the role of cats and dogs being
410 considered marginal (Hegglin and Deplazes, 2013). We confirmed these hypotheses by the

411 detection of *E. multilocularis* eggs after flotation, mainly in fox faeces in this study (27/32) and
412 only in 1/15 copro-samples from dogs and 1/5 from cats. Despite a low prevalence of *E.*
413 *multilocularis* DNA and eggs in dog faeces, the contribution of dogs in the transmission of *E.*
414 *multilocularis* to humans may be sizable due to their proximity with them and the presence of a
415 large amount of dog faeces downtown in the village studied (Liccioli et al., 2015a; Knapp et al.,
416 2018). Thus, the exposure risk related to domestic carnivores has to be more carefully considered.
417 We are planning further studies based on in vivo experiments in mice to assess the infectivity of *E.*
418 *multilocularis* eggs originating from cat and dog faeces from our study site.

419 Despite the low number of faeces containing *E. multilocularis* eggs, their spatial distribution
420 was also overdispersed in the study area, with the same hotspot as faeces detected with *E.*
421 *multilocularis* DNA. Such *E. multilocularis* environmental contamination is likely to persist for
422 several months. Indeed, *E. multilocularis* eggs can survive for more than 1 year in cold conditions
423 (Veit et al., 1995). Our study confirms that contamination via the definitive host faeces on a local
424 scale is generally overdispersed (Giraudoux et al., 2002; Vaniscotte et al., 2011; Liccioli et al.,
425 2014; Knapp et al., 2018). The activity patterns and defecation behaviour of the definitive hosts
426 have been suggested as possible causes of such micro-local hotspots of *E. multilocularis*
427 transmission to intermediate hosts and humans (Robardet et al., 2011; Giraudoux et al., 2013; Raoul
428 et al., 2015; Knapp et al., 2018). It cannot be excluded that, in the present study, only a small
429 number of individuals deposited multiple faeces collected in the field. It is therefore possible that
430 such spatial heterogeneity of environmental contamination by *E. multilocularis* was the
431 consequence of a very few individuals in the definitive host population (notably foxes) harbouring
432 almost the entire parasitic biomass (Raoul et al., 2001; Fischer et al., 2005). Individual
433 identification of collected faeces could thus allow us to know the true *E. multilocularis* prevalence
434 in a definitive host population in a non-invasive manner and to identify the contribution of each
435 individual to the environmental contamination (Liccioli et al., 2015b).

436 Our data suggest that *E. multilocularis* DNA and/or egg detection in carnivore faeces
437 (mainly that of foxes) is appropriate in ecological studies of *E. multilocularis* transmission, as their
438 spatial distribution presented the same characteristics. According to our results, *E. multilocularis*
439 egg detection from *E. multilocularis*-positive qPCR samples is especially useful in evaluating
440 exposure due to infected domestic animals which have close contact with humans.

441

442 **Acknowledgements**

443 This work was supported by the "Zones Ateliers" network ([https://inee.cnrs.fr/fr/zones-](https://inee.cnrs.fr/fr/zones-ateliers)
444 [ateliers](https://inee.cnrs.fr/fr/zones-ateliers)) and carried out in the "Zone Atelier Arc Jurassien" (<http://zaaj.univ-fcomte.fr>), France.
445 This work was also supported by the "Région Franche-Comté" (France) through the purchase of the
446 Leica DMI3000-B micromanipulator equipment (Grant 2013 No. 903/5110/309). We would also
447 like to thank the "Maison des Sciences de l'Homme et de l'Environnement Claude Nicolas
448 Ledoux" (France) for providing the Orthophotos.

449

451 **References**

- 452 Al-Sabi', M.N.S., Kapel, C.M.O., Deplazes, P., Mathis, A., 2007. Comparative copro-diagnosis of
 453 *Echinococcus multilocularis* in experimentally infected foxes. *Parasitol. Res.* 101, 731–736.
- 454 Bart, J.M., Knapp, J., Gottstein, B., El-Garch, F., Giraudoux, P., Glowatzki, M.L., Berthoud, H.,
 455 Maillard, S., Piarroux, R., 2006. EmsB, a tandem repeated multi-loci microsatellite, new
 456 tool to investigate the genetic diversity of *Echinococcus multilocularis*. *Infect. Genet. Evol.*
 457 6, 390–400.
- 458 Carlsbart, J., Roepstorff, A., Nejsum, P., 2008. Multiplex PCR on single unembryonated *Ascaris*
 459 (roundworm) eggs. *Parasitol. Res.* 104, 939.
- 460 Combes, B., Comte, S., Raton, V., Raoul, F., Boué, F., Umhang, G., Favier, S., Dunoyer, C.,
 461 Woronoff, N., Giraudoux, P., 2012. Westward spread of *Echinococcus multilocularis* in
 462 foxes, France, 2005–2010. *Emerg. Infect. Dis.* 18, 2059–2062.
- 463 Conraths, F.J., Deplazes, P., 2015. *Echinococcus multilocularis*: Epidemiology, surveillance and
 464 state-of-the-art diagnostics from a veterinary public health perspective. *Vet. Parasitol.* 213,
 465 149–161.
- 466 Davidson, R.K., Øines, Ø., Madslien, K., Mathis, A., 2009. *Echinococcus multilocularis*—
 467 adaptation of a worm egg isolation procedure coupled with a multiplex PCR assay to carry
 468 out large-scale screening of red foxes (*Vulpes vulpes*) in Norway. *Parasitol. Res.* 104, 509–
 469 514.
- 470 Deplazes, P., Dinkel, A., Mathis, A., 2003. Molecular tools for studies on the transmission biology
 471 of *Echinococcus multilocularis*. *Parasitology* 127, S53–S61.
- 472 Deplazes, P., Rinaldi, L., Alvarez Rojas, C.A., Torgerson, P.R., Harandi, M.F., Romig, T.,
 473 Antolova, D., Schurer, J.M., Lahmar, S., Cringoli, G., Magambo, J., Thompson, R.C.A.,

474 Jenkins, E.J., 2017. Global distribution of alveolar and cystic echinococcosis. *Adv.*
 475 *Parasitol.* 95, 315–493.

476 Deplazes, P., van Knapen, F., Schweiger, A., Overgaaauw, P.A.M., 2011. Role of pet dogs and cats
 477 in the transmission of helminthic zoonoses in Europe, with a focus on echinococcosis and
 478 toxocarosis. *Vet. Parasitol.*, 182, 41–53.

479 Dinkel, A., von Nickisch-Rosenegk, M., Bilger, B., Merli, M., Lucius, R., Romig, T., 1998.
 480 Detection of *Echinococcus multilocularis* in the definitive host: coprodiagnosis by PCR as
 481 an alternative to necropsy. *J. Clin. Microbiol.* 36, 1871–1876.

482 Dryden, M.W., Payne, P.A., Ridley, R., Smith, V., 2005. Comparison of common fecal flotation
 483 techniques for the recovery of parasite eggs and oocysts. *Vet. Ther.* 6, 14.

484 Dyachenko, V., Pantchev, N., Gawlowska, S., Vrhovec, M.G., Bauer, C., 2008. *Echinococcus*
 485 *multilocularis* infections in domestic dogs and cats from Germany and other European
 486 countries. *Vet. Parasitol.* 157, 244–253.

487 Escotte-Binet, S., Da Silva, A.M., Cancès, B., Aubert, D., Dubey, J., La Carbona, S., Villena, I.,
 488 Poulle, M.-L., 2019. A rapid and sensitive method to detect *Toxoplasma gondii* oocysts in
 489 soil samples. *Vet. Parasitol.* 274, 108904.

490 Fahrion, A.S., Schnyder, M., Wichert, B., Deplazes, P., 2011. *Toxocara* eggs shed by dogs and cats
 491 and their molecular and morphometric species-specific identification: is the finding of *T.*
 492 *cati* eggs shed by dogs of epidemiological relevance? *Vet. Parasitol.* 177, 186–189.

493 Farrell, L.E., Roman, J., Sunquist, M.E., 2000. Dietary separation of sympatric carnivores identified
 494 by molecular analysis of scats. *Mol. Ecol.* 9, 1583–1590.

495 Fischer, C., Reperant, L.A., Weber, J.M., Hegglin, D., Deplazes, P., 2005. *Echinococcus*
 496 *multilocularis* infections of rural, residential and urban foxes (*Vulpes vulpes*) in the canton
 497 of Geneva, Switzerland. *Parasite* 12, 339–346.

498 Fluss, R., Faraggi, D., Reiser, B., 2005. Estimation of the Youden index and its associated cutoff
 499 Point. *Biom. J.* 47, 458–472.

500 Frenkel, J.K., Parker, B.B., 1996. An apparent role of dogs in the transmission of *Toxoplasma*
501 *gondii*. The probable importance of xenosmophilia. Ann. N. Y. Acad. Sci. 791, 402–407.

502 Gasser, R.B., Chilton, N.B., Hoste, H., Beveridge, I., 1993. Rapid sequencing of rDNA from single
503 worms and eggs of parasitic helminths. Nucleic Acids Res. 21, 2525–2526.

504 Georges, S., Villard, O., Filisetti, D., Mathis, A., Marcellin, L., Hansmann, Y., Candolfi, E., 2004.
505 Usefulness of PCR analysis for diagnosis of alveolar echinococcosis with unusual
506 localizations: two case studies. J. Clin. Microbiol. 42, 5954–5956.

507 Giraudoux, P., Delattre, P., Takahashi, K., Raoul, F., Quere, J.P., Craig, P., Vuitton, D.A., 2002.
508 Transmission ecology of *Echinococcus multilocularis* in wildlife: what can be learned from
509 comparative studies and multiscale approaches? In: Craig, P.S. and Pawlowski, Z. (Eds.),
510 Cestode Zoonoses: Echinococcosis and Cysticercosis: An Emergent and Global Problem,
511 Nato Science Series, Sub-Series. I: Life and Behavioural Sciences. IOS Press, Amsterdam,
512 pp. 251–266.

513 Giraudoux, P., Raoul, F., Afonso, E., Ziadinov, I., Yang, Y., Li, L., Li, T., Quéré, J.-P., Feng, X.,
514 Wang, Q., Wen, H., Ito, A., Craig, P.S., 2013. Transmission ecosystems of *Echinococcus*
515 *multilocularis* in China and Central Asia. Parasitology 140, 1655–1666.

516 Hegglin, D., Deplazes, P., 2013. Control of *Echinococcus multilocularis*: strategies, feasibility and
517 cost–benefit analyses. Int. J. Parasitol. 43, 327–337.

518 Janko, C., Schröder, W., Linke, S., König, A., 2012. Space use and resting site selection of red
519 foxes (*Vulpes vulpes*) living near villages and small towns in Southern Germany. Acta
520 Theriol. (Warsz.) 57, 245–250.

521 Kapel, C.M.O., Torgerson, P.R., Thompson, R.C.A., Deplazes, P., 2006. Reproductive potential of
522 *Echinococcus multilocularis* in experimentally infected foxes, dogs, raccoon dogs and cats.
523 Int. J. Parasitol. 36, 79–86.

524 Karamon, J., Sroka, J., Dąbrowska, J., Bilska-Zajac, E., Zdybel, J., Kochanowski, M., Różycki, M.,
525 Cencek, T., 2019. First report of *Echinococcus multilocularis* in cats in Poland: a monitoring

526 study in cats and dogs from a rural area and animal shelter in a highly endemic region.
 527 Parasit. Vectors 12, 313.

528 Knapp, J., Bart, J.-M., Giraudoux, P., Glowatzki, M.-L., Breyer, I., Raoul, F., Deplazes, P.,
 529 Duscher, G., Martinek, K., Dubinsky, P., Guislain, M.-H., Cliquet, F., Romig, T.,
 530 Malczewski, A., Gottstein, B., Piarroux, R., 2009. Genetic diversity of the cestode
 531 *Echinococcus multilocularis* in red foxes at a continental scale in Europe. PLoS Negl. Trop.
 532 Dis. 3.

533 Knapp, J., Bart, J.M., Glowatzki, M.L., Ito, A., Gerard, S., Maillard, S., Piarroux, R., Gottstein, B.,
 534 2007. Assessment of use of microsatellite polymorphism analysis for improving spatial
 535 distribution tracking of *Echinococcus multilocularis*. J. Clin. Microbiol. 45, 2943–2950.

536 Knapp, J., Combes, B., Umhang, G., Aknouche, S., Millon, L., 2016a. Could the domestic cat play
 537 a significant role in the transmission of *Echinococcus multilocularis*? A study based on
 538 qPCR analysis of cat feces in a rural area in France. Parasite 23, 42.

539 Knapp, J., Giraudoux, P., Combes, B., Umhang, G., Boué, F., Said-Ali, Z., Aknouche, S., Garcia,
 540 C., Vacheyrou, M., Laboissière, A., Raton, V., Comte, S., Favier, S., Demerson, J.-M.,
 541 Caillot, C., Millon, L., Raoul, F., 2018. Rural and urban distribution of wild and domestic
 542 carnivore stools in the context of *Echinococcus multilocularis* environmental exposure. Int.
 543 J. Parasitol. 48, 937–946.

544 Knapp, J., Millon, L., Mouzon, L., Umhang, G., Raoul, F., Ali, Z.S., Combes, B., Comte, S.,
 545 Gbaguidi-Haore, H., Grenouillet, F., Giraudoux, P., 2014. Real time PCR to detect the
 546 environmental faecal contamination by *Echinococcus multilocularis* from red fox stools.
 547 Vet. Parasitol. 201, 40–47.

548 Knapp J., Umhang, G., Poulle, M.-L., Millon, L., 2016b. development of a real-time PCR for a
 549 sensitive one-step coprodiagnosis allowing both the identification of carnivore feces and the
 550 detection of *Toxocara* spp. and *Echinococcus multilocularis*. Appl. Environ. Microbiol. 82,
 551 2950–2958.

552 Kovach, A.I., Litvaitis, M.K., Litvaitis, J.A., 2003. Evaluation of fecal mtDNA analysis as a method
553 to determine the geographic distribution of a rare lagomorph. *Wildl. Soc. Bull.* 1973-2006
554 31, 1061–1065.

555 Krauze-Gryz, D., Gryz, J.B., Goszczyński, J., Chylarecki, P., Zmihorski, M., 2012. The good, the
556 bad, and the ugly: space use and intraguild interactions among three opportunistic
557 predators—cat (*Felis catus*), dog (*Canis lupus familiaris*), and red fox (*Vulpes vulpes*)—
558 under human pressure. *Can. J. Zool.* 90, 1402–1413.

559 Kulldorff, M., Nagarwalla, N., 1995. Spatial disease clusters: detection and inference. *Stat. Med.*
560 14, 799–810.

561 Li, W., Guo, Z., Duo, H., Fu, Y., Peng, M., Shen, X., Tsukada, H., Irie, T., Nasu, T., Horii, Y.,
562 Nonaka, N., 2013. Survey on helminths in the small intestine of wild foxes in Qinghai,
563 China. *J. Vet. Med. Sci.* 75, 1329–1333.

564 Liccioli, S., Giraudoux, P., Deplazes, P., Massolo, A., 2015a. Wilderness in the ‘city’ revisited:
565 different urbes shape transmission of *Echinococcus multilocularis* by altering predator and
566 prey communities. *Trends Parasitol.* 31, 297–305.

567 Liccioli, S., Kutz, S.J., Ruckstuhl, K.E., Massolo, A., 2014. Spatial heterogeneity and temporal
568 variations in *Echinococcus multilocularis* infections in wild hosts in a North American
569 urban setting. *Int. J. Parasitol.* 44, 457–465.

570 Liccioli, S., Rogers, S., Greco, C., Kutz, S.J., Chan, F., Ruckstuhl, K.E., Massolo, A., 2015b.
571 Assessing individual patterns of *Echinococcus multilocularis* infection in urban coyotes:
572 non-invasive genetic sampling as an epidemiological tool. *J. Appl. Ecol.* 52, 434–442.

573 Mathis, A., Deplazes, P., Eckert, J., 1996. An improved test system for PCR-based specific
574 detection of *Echinococcus multilocularis* eggs. *J. Helminthol.* 70, 219.

575 Matsuo, K., Kamiya, H., 2005. Modified sugar centrifugal flotation technique for recovering
576 *Echinococcus multilocularis* eggs from soil. *J. Parasitol.* 91, 208–209.

577 Nijse, R., Mughini-Gras, L., Wagenaar, J.A., Franssen, F., Ploeger, H.W., 2015. Environmental
578 contamination with *Toxocara* eggs: a quantitative approach to estimate the relative
579 contributions of dogs, cats and foxes, and to assess the efficacy of advised interventions in
580 dogs. *Parasit. Vectors* 8, 397.

581 Nonaka, N., Sano, T., Inoue, T., Teresa Armua, M., Fukui, D., Katakura, K., Oku, Y., 2009.
582 Multiplex PCR system for identifying the carnivore origins of faeces for an epidemiological
583 study on *Echinococcus multilocularis* in Hokkaido, Japan. *Parasitol. Res.* 106, 75–83.

584 Øines, Ø., Isaksson, M., Hagström, Å., Tavoranpanich, S., Davidson, R.K., 2014. Laboratory
585 assessment of sensitive molecular tools for detection of low levels of *Echinococcus*
586 *multilocularis*-eggs in fox (*Vulpes vulpes*) faeces. *Parasit. Vectors* 7, 246.

587 Piarroux, M., Gaudart, J., Bresson-Hadni, S., Bardonnnet, K., Faucher, B., Grenouillet, F., Knapp, J.,
588 Dumortier, J., Watelet, J., Gerard, A., Beytout, J., Abergel, A., Wallon, M., Vuitton, D.A.,
589 Piarroux, R., FrancEchino network, 2015. Landscape and climatic characteristics associated
590 with human alveolar echinococcosis in France, 1982 to 2007. *Eurosurveillance* 20, 21118.

591 Piarroux, M., Piarroux, R., Knapp, J., Bardonnnet, K., Dumortier, J., Watelet, J., Gerard, A., Beytout,
592 J., Abergel, A., Bresson-Hadni, S., Gaudart, J., 2013. Populations at risk for alveolar
593 echinococcosis, France. *Emerg. Infect. Dis.* 19, 721–728.

594 Poulle, M.-L., Bastien, M., Richard, Y., Josse-Dupuis, É., Aubert, D., Villena, I., Knapp, J., 2017.
595 Detection of *Echinococcus multilocularis* and other foodborne parasites in fox, cat and dog
596 faeces collected in kitchen gardens in a highly endemic area for alveolar echinococcosis.
597 *Parasite* 24, 29.

598 Raoul, F., Deplazes, P., Nonaka, N., Piarroux, R., Vuitton, D., Giraudoux, P., 2001. Assessment of
599 the epidemiological status of *Echinococcus multilocularis* in foxes in France using ELISA
600 coprotests on fox faeces collected in the field. *Int. J. Parasitol.* 31, 1579–1588.

601 Raoul, F., Hegglin, D., Giraudoux, P., 2015. Trophic ecology, behaviour and host population
602 dynamics in *Echinococcus multilocularis* transmission. *Vet. Parasitol.* 213, 162–171.

603 Robardet, E., Giraudoux, P., Caillot, C., Augot, D., Boue, F., Barrat, J., 2011. Fox defecation
604 behaviour in relation to spatial distribution of voles in an urbanised area: an increasing risk
605 of transmission of *Echinococcus multilocularis*? Int. J. Parasitol. 41, 145–154.

606 Robin, X., Turck, N., Hainard, A., Tiberti, N., Lisacek, F., Sanchez, J.-C., Müller, M., 2011. pROC:
607 an open-source package for R and S+ to analyze and compare ROC curves. BMC
608 Bioinformatics 12, 77.

609 Sanger, F., Nicklen, S., Coulson, A.R., 1992. DNA sequencing with chain-terminating inhibitors.
610 1977. Biotechnol. Read. Mass 24, 104–108.

611 Scott, D.M., Berg, M.J., Tolhurst, B.A., Chauvenet, A.L.M., Smith, G.C., Neaves, K., Lochhead, J.,
612 Baker, P.J., 2014. Changes in the distribution of red foxes (*Vulpes vulpes*) in urban areas in
613 Great Britain: findings and limitations of a media-driven nationwide survey. PLoS ONE 9,
614 e99059.

615 Štefanić, S., Shaikenov, B.S., Deplazes, P., Dinkel, A., Torgerson, P.R., Mathis, A., 2004.
616 Polymerase chain reaction for detection of patent infections of *Echinococcus granulosus*
617 (“sheep strain”) in naturally infected dogs. Parasitol. Res. 92, 347–351.

618 Stieger, C., Hegglin, D., Schwarzenbach, G., Mathis, A., Deplazes, P., 2002. Spatial and temporal
619 aspects of urban transmission of *Echinococcus multilocularis*. Parasitology 124, 631–640.

620 Trachsel, D., Deplazes, P., Mathis, A., 2007. Identification of taeniid eggs in the faeces from
621 carnivores based on multiplex PCR using targets in mitochondrial DNA. Parasitology 134,
622 911–920.

623 Tylkowska, A., Pilarczyk, B., Pilarczyk, R., Zyśko, M., Tomza-Marciniak, A., 2019. Presence of
624 tapeworms (Cestoda) in Red Fox (*Vulpes Vulpes*) in North-western Poland, with particular
625 emphasis on *Echinococcus Multilocularis*. J. Vet. Res. 63, 71–78.

626 Umhang G., Comte, S., Raton, V., Hormaz, V., Boucher, J.-M., Favier, S., Combes, B., Boué, F.,
627 2014. *Echinococcus multilocularis* infections in dogs from urban and peri-urban areas in
628 France. Parasitol. Res. 113, 2219–2222.

629 Umhang, G., Bastien, M., Renault, C., Faisse, M., Caillot, C., Boucher, J.-M., Hormaz, V., Poulle,
 630 M.-L., Boué, F., 2017. A flotation/sieving method to detect *Echinococcus multilocularis* and
 631 *Toxocara* spp. eggs in soil by real-time PCR. *Parasite* 24, 28.

632 Umhang, G., Forin-Wiart, M.-A., Hormaz, V., Caillot, C., Boucher, J.-M., Poulle, M.-L., Boué, F.,
 633 2015. *Echinococcus multilocularis* detection in the intestines and feces of free-ranging
 634 domestic cats (*Felis s. catus*) and European wildcats (*Felis s. silvestris*) from northeastern
 635 France. *Vet. Parasitol.* 214, 75–79.

636 Umhang, G., Knapp, J., Hormaz, V., Raoul, F., Boué, F., 2014. Using the genetics of *Echinococcus*
 637 *multilocularis* to trace the history of expansion from an endemic area. *Infect. Genet. Evol.*
 638 22, 142–149.

639 Umhang, G., Raton, V., Comte, S., Hormaz, V., Boucher, J.-M., Combes, B., Boué, F., 2012.
 640 *Echinococcus multilocularis* in dogs from two French endemic areas: No evidence of
 641 infection but hazardous deworming practices. *Vet. Parasitol.* 188, 301–305.

642 Valot, B., Knapp, J., Umhang, G., Grenouillet, F., Millon, L., 2015. Genomic characterization of
 643 EmsB microsatellite loci in *Echinococcus multilocularis*. *Infect. Genet. Evol.* 32, 338–341.

644 Vaniscotte, A., Raoul, F., Poulle, M.L., Romig, T., Dinkel, A., Takahashi, K., Guislain, M.H.,
 645 Moss, J., Tiaoying, L., Wang, Q., Qiu, J., Craig, P.S., Giraudoux, P., 2011. Role of dog
 646 behaviour and environmental fecal contamination in transmission of *Echinococcus*
 647 *multilocularis* in Tibetan communities. *Parasitology* 138, 1316–1329.

648 Veit, P., Bilger, B., Schad, V., Schäfer, J., Frank, W., Lucius, R., 1995. Influence of environmental
 649 factors on the infectivity of *Echinococcus multilocularis* eggs. *Parasitology* 110, 79–86.

650

651

652

653

654 **Figure legends**

655

656 **Fig. 1.** The predetermined circuit (red dash) of carnivore faeces collection on the study site (a rural
657 town in the eastern part of France (006°26'46"E, 46°56'53"N)).

658

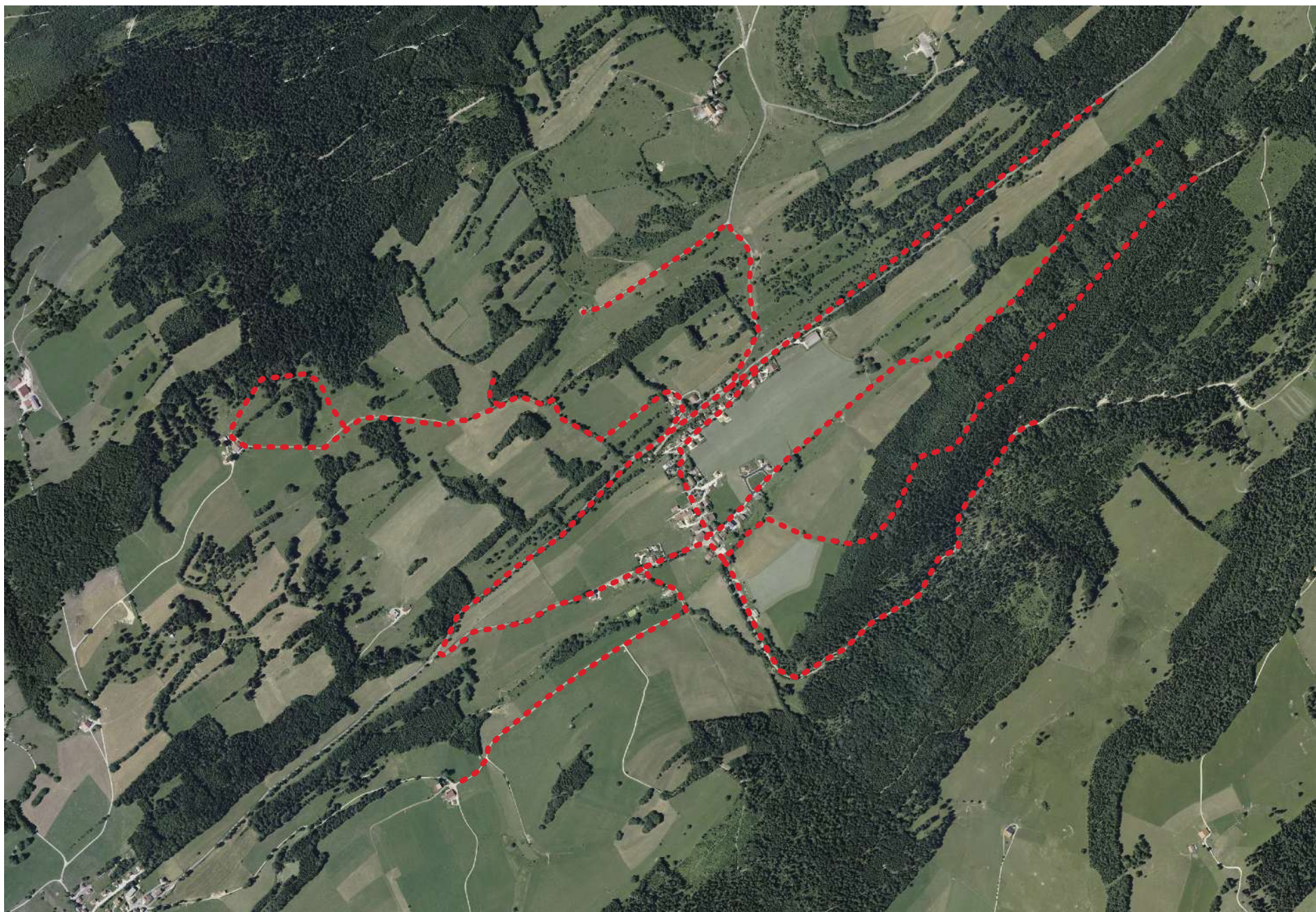
659 **Fig. 2.** Workflow of *Echinococcus multilocularis* DNA and egg detection in carnivore faeces.
660 Screening and flotation were performed using 0.5 and 5 g of faeces, respectively. qPCR, real-time
661 quantitative PCR.

662

663 **Fig. 3.** Relationship between quantitative cycle (Cq) values obtained from *Echinococcus*
664 *multilocularis*-specific real-time quantitative PCR (*E. multilocularis* qPCR) performed on carnivore
665 faeces containing *E. multilocularis* eggs (*E. multilocularis* egg (+)) or not (*E. multilocularis* egg (-
666)). (A) Distribution of faeces containing *E. multilocularis* eggs, or not, according to the Cq values of
667 *E. multilocularis*- specific qPCRs. N, n: sample size. Boxes represent the inter-quartile distances;
668 thick lines, the medians; whiskers, the extremes values; crosses, the means; and circles, outliers.
669 Statistical significance was determined using the non-parametric Mann-Whitney U Test. ****P* =
670 0.001. (B) Receiver Operating Characteristic (ROC) curve of the *E. multilocularis*-specific qPCR
671 Cq values to predict the presence/absence of *E. multilocularis* eggs (area under ROC curve (AUC)
672 = 0.73). The optimal threshold by the Youden index Cq = 38.365, corresponding to a sensitivity of
673 81% (95% Confidence interval (CI): 66-94%) and a specificity of 69% (95% CI: 58-80%).

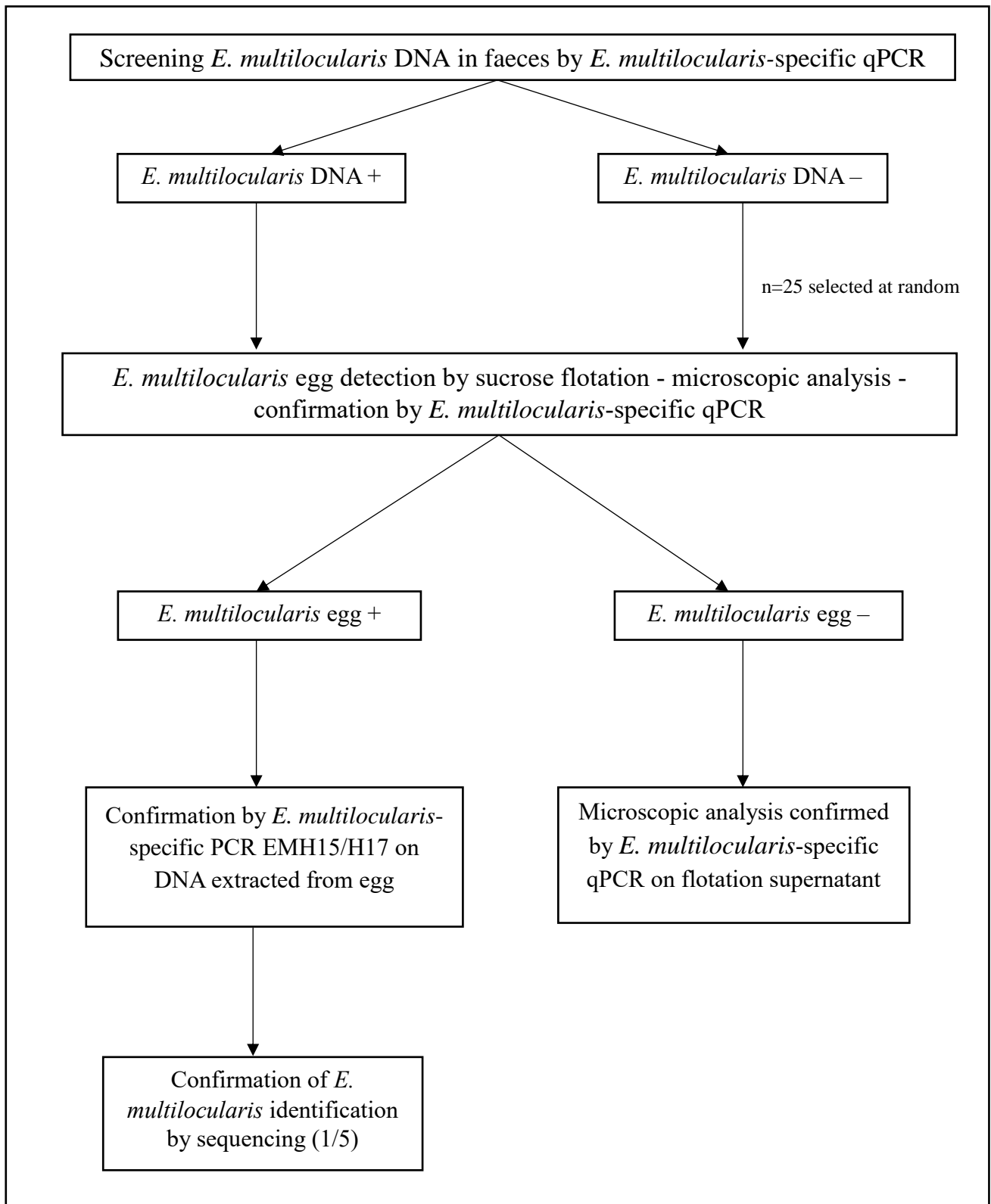
674

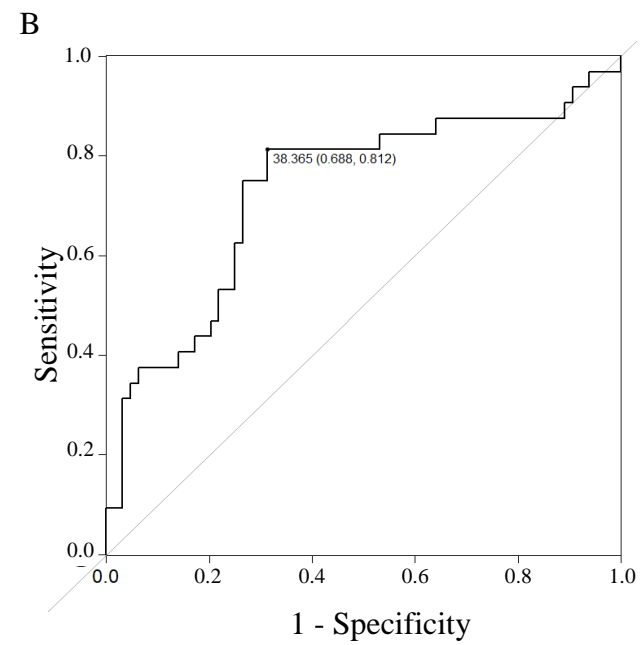
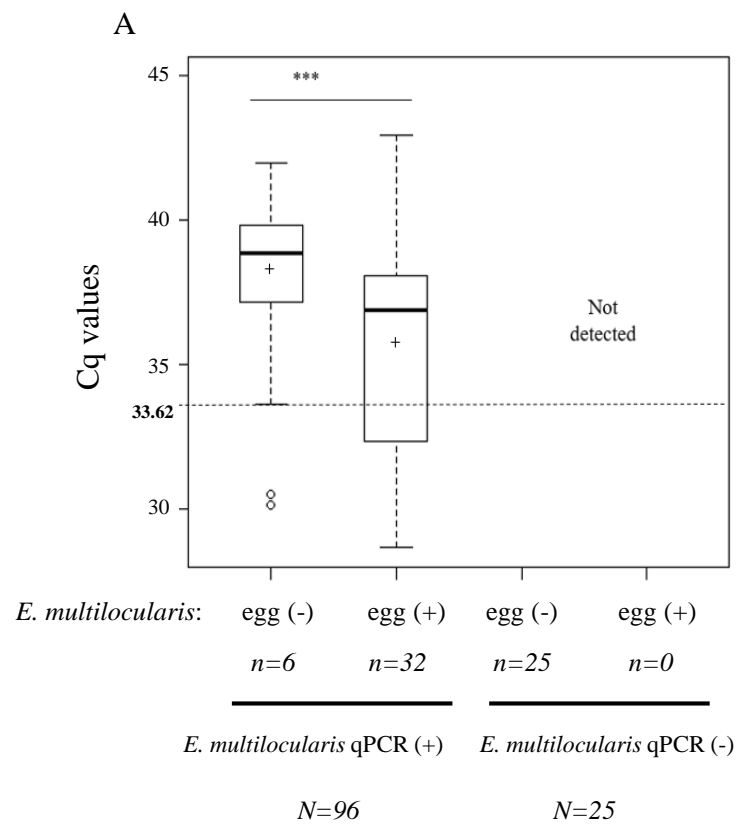
675 **Fig. 4.** Kulldorff statistics on the distribution of carnivore faeces in the studied site in France, from
676 *Echinococcus multilocularis* DNA-positive faeces (Aa, Ba, Ca) and *E. multilocularis* egg-positive
677 faeces (Ab, Bb, Cb). (A) All carnivore faeces collected; (B) fox faeces; (C) dog and cat faeces.



0 500 1000 m

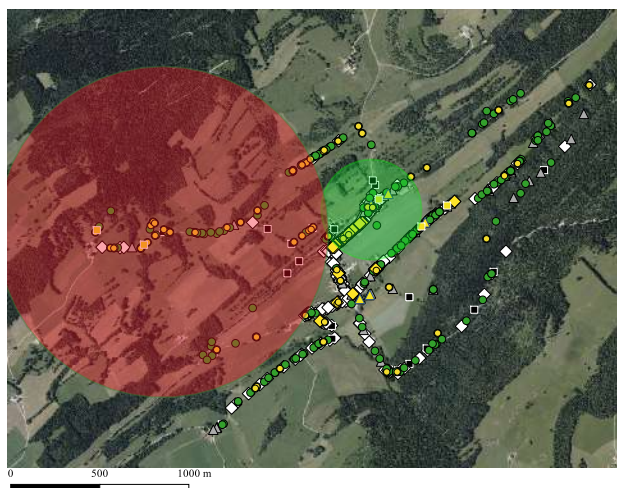




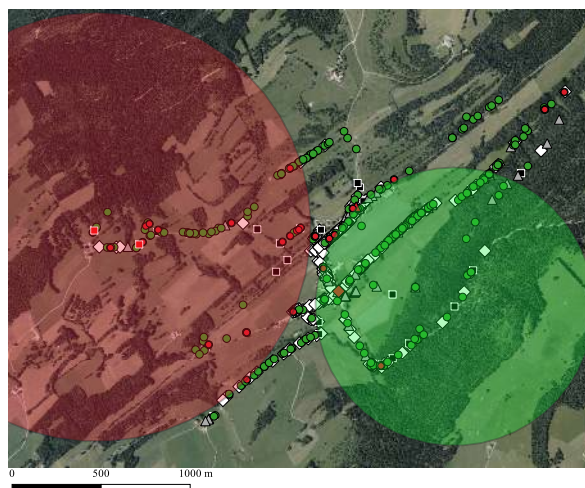


A

a

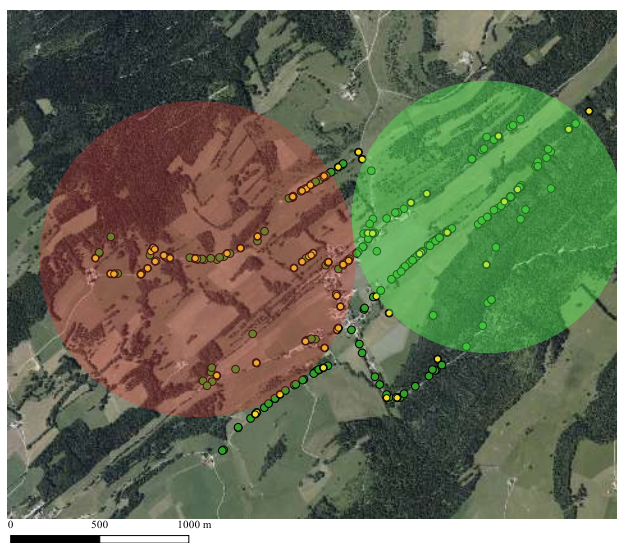


b

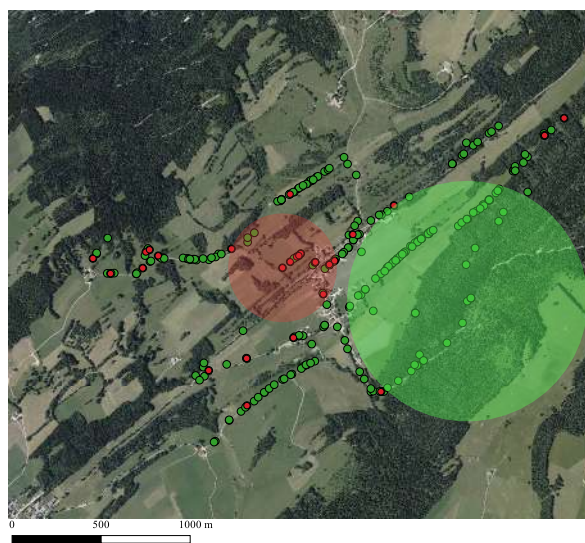


B

a

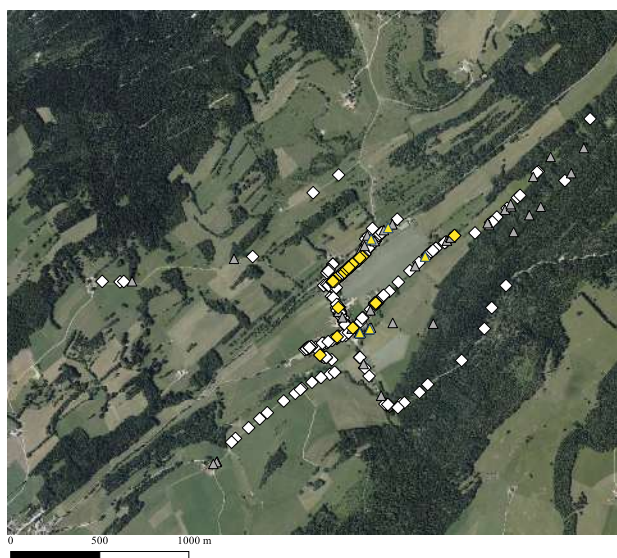


b

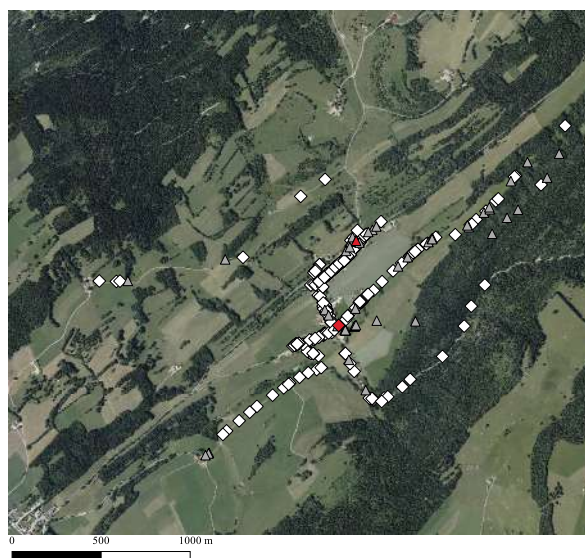


C

a



b



Faeces :

Negative

E. multilocularis
DNA +*E. multilocularis*
eggs +

Clusters :

 High rate

 Low rate

Fox

●

●

●

Dog

◇

◇

◇

Cat

△

△

△

Undetermined

■

■

■

Table 1. Comparison between faeces identification based on morphological criteria (shape, size, and composition) and faeces identification based on molecular analysis (by species-specific real-time quantitative PCRs)

Morphological identification	Molecular identification				Total
	Fox	Dog	Cat	Undetermined	
Fox	220 (68.3%)	39 (12.1%)	32 (10.0%)	31 (9.6%)	322
Dog	38 (8.7%)	374 (85.8%)	10 (2.3%)	14 (3.2%)	436
Cat	5 (21.7%)	5 (21.7%)	12 (52.2%)	1 (4.4%)	23
Mustelids	14 (56.0%)	7 (28.0%)	0 (0.0%)	4 (16.0%)	25
Undetermined	1 (12.5%)	6 (75.0%)	0 (0.0%)	1 (12.5%)	8
Total	278	431	54	51	814

Bold values indicate occurrence of faeces per species for which morphological identification was confirmed by molecular analysis.

Table 2. Method sensitivities (in %) of the sucrose flotation technique combined with microscopic observation and detection by specific real-time quantitative PCR (qPCR) for *Echinococcus multilocularis* in frozen copro-samples (5 g). For each number of *E. multilocularis* eggs, three samples were used.

Number of eggs	Microscopic observation	qPCR <i>E. multilocularis</i>
0	-	00.0% (0/3)
1	00.0% (0/3)	33.3% (1/3)
3	00.0% (0/3)	33.3% (1/3)
5	33.3% (1/3)	66.7% (2/3)
10	100.0% (3/3)	100.0% (3/3)

Table 3. Detection of *Echinococcus multilocularis* DNA and eggs in carnivore host faecal samples collected between March 2017 and November 2018 in a rural town in the eastern part of France.

Host identification	Fox	Dog	Cat	Undetermined	Total
Total sampled	278	431	54	51	814
qPCR <i>E. multilocularis</i> (number of positive samples)	70	15	5	6	96
Prevalence %	25.2	3.5	9.3	11.7	11.8
95% CI	(20.3-30.8)	(2.0-5.8)	(3.5-21.1)	(4.9-24.6)	(9.7-14.3)
<i>E. multilocularis</i> egg-positive samples	27	1	1	3	32

qPCR, real-time quantitative PCR; CI, Confidence Interval.

Echinococcus multilocularis
eggs confirmation by PCRs

Flotation, taeniid egg sampling

Hosts and *Echinococcus multilocularis* real-time PCRs

Copro-sampling, geolocation



Echinococcus multilocularis
spatial distribution